NOTES AND CORRESPONDENCE

Evaluation of Temperature Differences for Paired Stations of the U.S. Climate Reference Network

Kevin P. Gallo*

NOAA/NESDIS, Camp Springs, Maryland

(Manuscript received 7 January 2004, in final form 18 June 2004)

ABSTRACT

Adjustments to data observed at pairs of climate stations have been recommended to remove the biases introduced by differences between the stations in time of observation, temperature instrumentation, latitude, and elevation. A new network of climate stations, located in rural settings, permits comparisons of temperatures for several pairs of stations without two of the biases (time of observation and instrumentation). The daily, monthly, and annual minimum, maximum, and mean temperatures were compared for five pairs of stations included in the U.S. Climate Reference Network. Significant differences were found between the paired stations in the annual minimum, maximum, and mean temperatures for all five pairs of stations. Adjustments for latitude and elevation differences contributed to greater differences in mean annual temperature for four of the five stations. Lapse rates computed from the mean annual temperature differences between station pairs differed from a constant value, whether or not latitude adjustments were made to the data. The results suggest that microclimate influences on temperatures observed at nearby (horizontally and vertically) stations are potentially much greater than influences that might be due to latitude or elevation differences between the stations.

1. Introduction

The analysis of temperature observations from pairs of stations has been a popular method for climate analysis of urban and rural temperature differences (e.g., Kukla et al. 1986; Karl et al. 1988; Gallo et al. 1993; Gallo and Owen 1999). In an analysis of urban and rural temperature differences by Peterson (2003), several approximated adjustments were made to the urban and rural station in situ mean annual air temperature data prior to the urban and rural station comparisons. These adjustments were made in an attempt to account for biases in the data observed at the stations due to differences in elevation, latitude, time of observation, and instrumentation.

A relatively new network of long-term climate observation stations, the U.S. Climate Reference Network (CRN; available online at http://www.ncdc.noaa.gov/oa/climate/uscrn/), includes several sites with stations located relatively close to each other. The data available from these stations are not subject to several of the biases (instrument differences or time of observation) cited by Peterson (2003) such that these data can be used to more thoroughly examine the microclimatic differences between stations, specifically differences in temperatures and the environmental lapse rates for pairs of stations. The objectives of this study include an assessment of daily, monthly, and annual temperatures, as well as environmental lapse rates, for pairs of CRN stations.

2. Methodology

The CRN stations were located following a site selection criteria that included consideration of the sites' regional representation of climate, location sensitivity to measurement of long-term climate variability, and local environmental factors that might influence the quality of measurements (NOAA/NESDIS 2002). The distance between the pairs of CRN stations included in this study varied from 4.9 to 29.7 km (Table 1).

The CRN station data utilized in this study include hourly reports of average temperature measured by three sensors. The temperature sensors utilized at all CRN stations are identical (currently fan-aspirated and shielded platinum resistance thermometers, mounted 1.5 m above the ground surface), thus no instrument

Corresponding author address: Dr. Kevin P. Gallo, USGS National Center for Earth Resources Observation and Science (EROS) Data Center, 47914 252nd Street, Sioux Falls, SD 57198. E-mail: kgallo@usgs.gov

TABLE 1. Elevations, latitude, and longitude and period of analysis for the CRN station pairs utilized in this study. Latitude and elevation adjustments are applied to the station identified to adjust temperature data for biases. Horizontal distance between stations is identified.

Station	Elevation (m)	Latitude (°N)	Longitude (°W)	Study interval (start and end dates)	Latitude adjusted (°C)	Elevation adjusted (°C)	Station distance (km)
Asheville 8SSW (NC)	657.1	+35.4950	–82.6150	1 Jan–31 Dec 2002	+0.07	+0.09	9.9
Asheville 13S (NC)	639.6	+35.4185	–82.5567	1 Jan–31 Dec 2002			
Durham 2N (NH)	37.9	+43.1720	–70.9280	1 Jan–31 Dec 2002	+0.06	+0.08	7.3
Durham 2SSW (NH)	22.2	+43.1090	–70.9490	1 Jan–31 Dec 2002			
Lincoln 11SW (NE)	416.7	+40.6954	–96.8541	1 Mar 2002–28 Feb 2003	–0.14	+0.29	29.7
Lincoln 8ENE (NE)	361.6	+40.8484	–96.5651	1 Mar 2002–28 Feb 2003			
Stillwater 2W (OK)	277.5	+36.1347	–97.1415	1 Apr 2002–31 Mar 2003	+0.02	+0.03	4.9
Stillwater 5WNW (OK)	271.0	+36.1180	–97.0914	1 Apr 2002–31 Mar 2003			
Wolf Point 34NE (MT)	803.8	+48.4887	–105.2090	1 Jan–31 Dec 2002	+0.16	+0.90	21.6
Wolf Point 29ENE (MT)	634.0	+48.3082	–105.1018	1 Jan–31 Dec 2002			

bias exists when the data of two nearby CRN stations are compared.

The hourly average temperatures, derived from the mean of observations made at 5-min intervals, were used to derive daily 0001 through 2400 LST maximum and minimum temperatures. These maximum and minimum temperatures were then used to compute the daily mean temperatures. Thus, no time of observation bias exists is this dataset.

Slight (less than 0.2°) differences did exist between the latitudes of some of the CRN station pairs examined. A latitude adjustment of $-0.9°C$ per degree of northerly increase in latitude (Peterson 2003) was used to adjust the mean annual temperatures for the effect of latitude differences.

There also were observed differences in elevation between the pairs of stations that ranged from 6.5 to 170 m (Table 1). The adjustment of $-5.3°C\ km^{-1}$ increase in elevation (Peterson 2003) was used to adjust station annual mean temperatures for the effect of elevation differences.

Daily minimum, maximum, and mean temperatures of the five pairs of stations (Table 1) were derived over a 1-yr interval. This interval varied with the station pairs because of time of instrument installation. The hourly average temperatures reported for the three temperature sensors at the CRN stations were used in this analysis. Data were checked for anomalous values using the established CRN criteria that a sensor must not differ in temperature by more than 0.3°C from the other sensors (available online at http://www.ncdc.noaa.gov/oa/climate/uscrn/officialtemp.html). If the temperatures of all three sensors differed by $\leq 0.3°C$, the hourly temperature was computed as the mean of the three observed temperatures. If the temperatures of two of the three sensors differed by $\leq 0.3°C$, then the average was computed from the two sensors. If the hourly temperature for each sensor differed by more than 0.3°C from the others, this hourly observation was deleted. A complete record of 24 h of data was required for a day to be included in this analysis.

Three temperature datasets were then prepared for analysis. The first included the "unadjusted" daily minimum, maximum, and mean temperatures with no adjustments for latitude or elevation differences between the stations. The second, "latitude adjusted," included application of the Peterson (2003) adjustment to mean annual temperatures to adjust for latitude differences between the stations. The third, "fully adjusted," included both latitude and elevation adjustments (Peterson 2003) to the mean annual temperatures. The adjustments were applied to one of the stations in each pair of stations as indicated in Table 1. For all pairs of stations examined, the temperature differences were computed through subtraction of the temperature values of the second station of each pair listed in Table 1 from the first station. Thus, for the Asheville stations, the values for station 13S were subtracted from those of station 8SSW.

The unadjusted temperatures of the stations were compared on a daily, monthly, and annual basis. The latitude-adjusted mean annual temperatures were computed and used to derive an environmental lapse rate (ELR; $°C\ km^{-1}$) based on the elevation differences of the paired stations. Additionally, latitude- and elevation-adjusted mean annual temperatures were compared to the unadjusted temperatures.

3. Results and discussion

a. Local analysis: Lincoln, Nebraska

The CRN dataset contains a great deal of information that should stimulate microclimate research. The frequency distribution of minimum and maximum temperatures were examined for the two Lincoln, Nebraska, stations (Fig. 1). The most striking part of the minimum temperature distribution is the large number of observations that occur at 2400 LST for both of the stations. The relatively large number of occurrences of the minimum temperature being observed at 2400 LST is associated with movement of a cold front through the

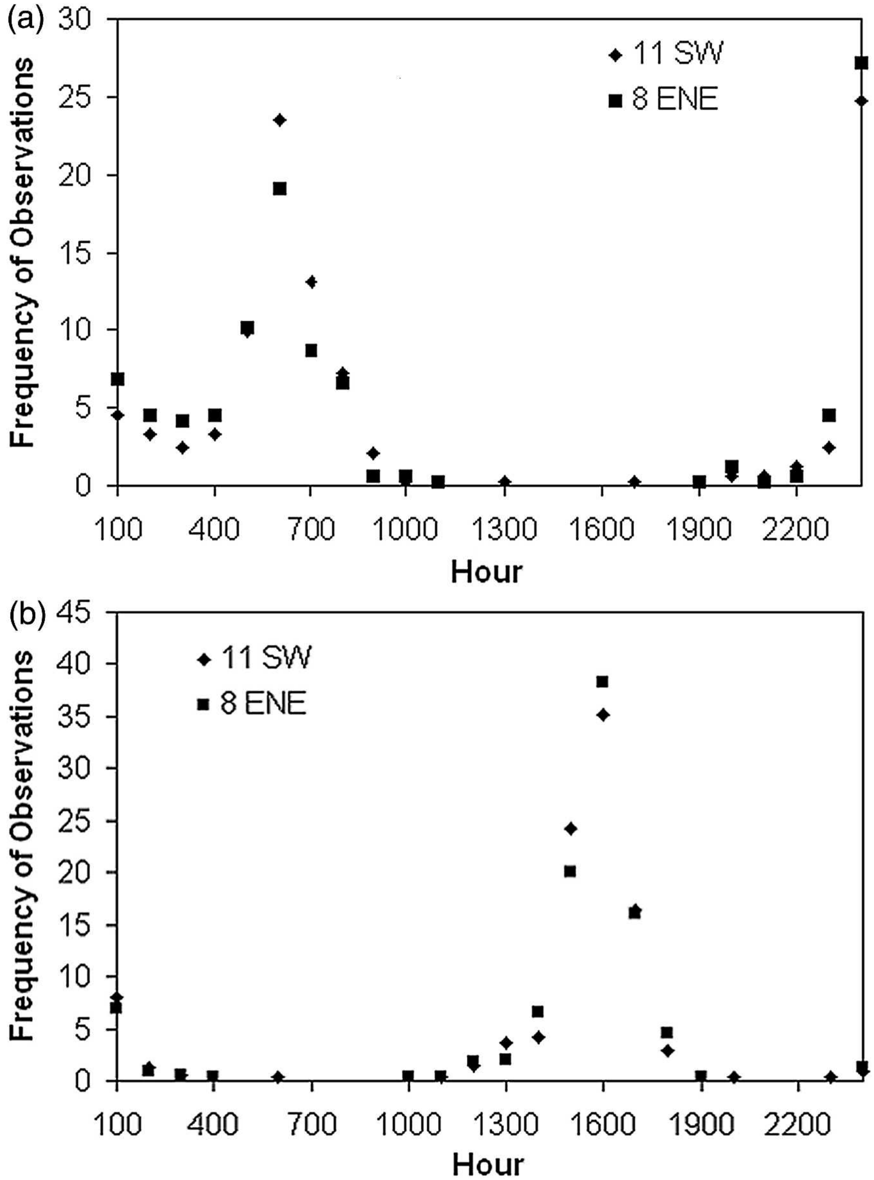

Fig. 1. Frequency of daily observation times of (top) minimum and (bottom) maximum temperatures for the two Lincoln stations.

region. As displayed in Fig. 2, for the Lincoln 11SW station, the minimum temperature on 8 January 2003 was 1.05°C at 0800 LST. An early morning low of 0.04°C was observed at 0800 LST on 9 January 2003, however, with the passage of a cold front at some time during that day, a minimum for that day of –2.2°C was observed at 2400 LST. Although a relative minimum was observed during the morning hours of 10 January 2003, again, the minimum temperature for the day was observed at 2400 LST. Similar frequency distributions were examined for the other station pairs included in this study. The Stillwater, Oklahoma, stations exhibited the greatest frequency of minimum temperatures at 0600 LST, with the 2400 LST observation time displaying the second greatest number of minimum temperatures. Although there were occasions when, in association with passage of a cold front, the maximum daily temperature was observed at 0100, for example, 10 January 2003 (Fig. 2), these events were not as frequent as the observation of minimum temperatures at 2400 LST.

The daily minimum and maximum temperatures of the two stations did not always occur at the same time (Fig. 1); however, the mean wind speed during the hour of observed minimum and maximum temperatures was retained for analysis. Differences in minimum and maximum temperature were examined as related to the wind speed at the Lincoln 8ENE station (Fig. 3). The

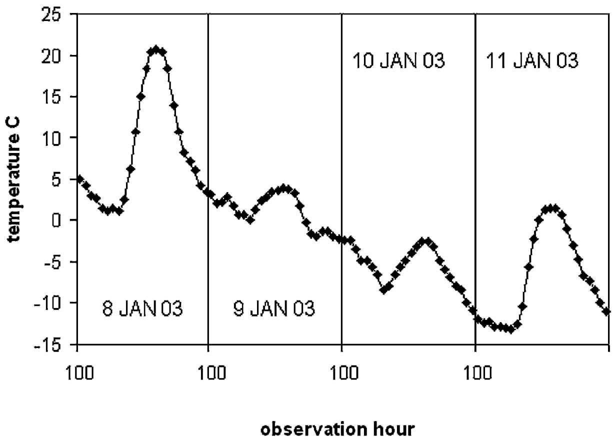

FIG. 2. Temperature (°C) observed at Lincoln 11SW station from 8 to 11 Jan 2003.

greatest minimum temperature differences, as might be expected, occurred with low or no observed wind speed. The maximum temperatures seemed relatively unaffected by wind speed. The annual mean difference (station 8ENE values subtracted from values of 11SW) in the unadjusted minimum temperatures for the Lincoln stations was 0.85°C (Table 2). The annual mean difference in unadjusted maximum temperatures for the paired stations was −0.24°C, and the difference in the unadjusted annual mean temperature was 0.30°C. Thus the station with the greater elevation actually displayed a warmer annual minimum temperature and warmer mean temperature than the station of lower elevation.

The Lincoln 11SW station was 0.15° south of, and 55.2 m greater in elevation, than the Lincoln 8ENE station. Thus, the fully adjusted (latitude and elevation adjustments) temperatures of the Lincoln 11SW included a latitude adjustment (Table 1) of −0.14°C (cooled to the more northerly latitude of Lincoln 8ENE) and an elevation adjustment (Table 1) of +0.29°C (warmed to the lower elevation of 8ENE) as per Peterson (2003). These adjustments result in the net addition of 0.15°C to the mean annual temperature values of station 11SW. Since the observed mean annual temperature at the 11SW station was already greater than that at the 8ENE station, these adjustments resulted in differences in the adjusted mean annual temperature that were greater than that of the unadjusted data (Table 2).

The local environment associated with the two Lincoln stations clearly contributed to the temperatures observed at these stations. The 8ENE station is located in an open area; however, it is surrounded by trees within 30 to 100 m of the instruments. The 11SW station is located in an unobstructed area. The mean wind speed at the observed times of minimum temperature was 0.6 m s^{-1} at the 8ENE station, compared to 2.1 m s^{-1} at the 11SW station, likely due to the trees in the vicinity of the 8ENE station. This reduction in wind speed (and the resultant reduction in atmospheric mixing and increase in radiational cooling) likely resulted in the lower minimum temperatures observed at the 8ENE station even though this station is over 50 m less in elevation than the 11SW station.

b. General analysis

1) TEMPERATURE DIFFERENCES BETWEEN PAIRS

The results of temperature adjustments for the remaining pairs of stations are included in Table 2. Similar to the Lincoln station pair, the station with the higher elevation exhibited a higher mean annual minimum temperature at the Durham, New Hampshire; Stillwater; and Wolf Point, Montana, sites as evidenced by the positive value of the differences between the station pairs. Only the Asheville, North Carolina, station pair exhibited a lower annual minimum temperature for the station with the greater elevation. Similar to the Lincoln pair, when the elevation and latitude adjustments are applied to the Durham, Stillwater, or Wolf Point annual mean temperatures, the difference values become greater for the adjusted data compared to the unadjusted data. The adjustments to the data resulted in greater differences in the mean temperatures for all stations except Asheville, where the difference between stations decreased from −0.53 to −0.37°C. A paired *t* test was applied to the minimum, maximum, and mean temperatures of each pair of stations, and all differences observed for the unadjusted data were significant.

When the monthly differences in unadjusted temperatures were examined for all five stations (not shown), 64% of the temperature differences between the pairs of stations were significantly different. The wind speeds at the time of minimum and maximum temperature observations appear, as in the Lincoln example, to be associated with some of the temperature differences observed between the stations. The wind speeds at the time of observed minimum temperatures were all greater at the stations with higher elevation (except for the Asheville pair). The difference in mean wind speed at the time of minimum temperature observation for the station pairs ranged from 0.2 (Durham pair) to 2.1 m s^{-1} (Wolf Point pair).

2) IMPLICATIONS OF RESULTS ON DERIVATION OF ENVIRONMENTAL LAPSE RATE

The mean annual ELRs were computed from the differences in the unadjusted and latitude-adjusted mean annual temperatures for each pair of stations. The ELR is of course dependent on accurate elevation data for the stations. The initial elevations for the CRN stations were reported as +/−30.5 m as measured with a global positioning system (GPS). The initial elevation values have since been updated using available maps.

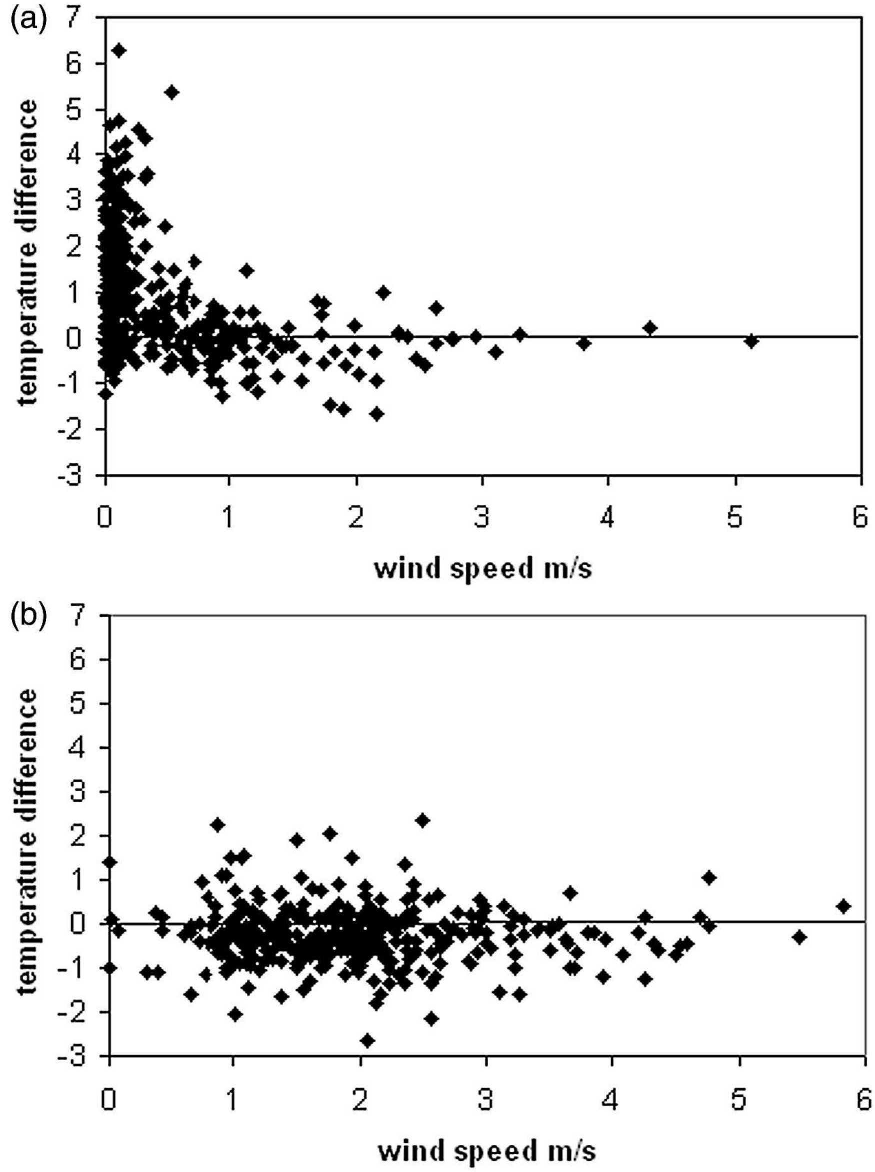

Fig. 3. Daily (top) minimum and (bottom) maximum temperature difference (°C) between Lincoln 11SW and Lincoln 8 ENE plotted as a function of the wind speed (m s^{-1}) observed at Lincoln 8ENE.

The U.S. Geological Survey (USGS) National Elevation Dataset (NED; Gesch et al. 2002) was used in this study to obtain elevation data for the stations. The NED (available online at http://gisdata.usgs.gov/website/Map_Studio/viewer.asp) provides elevations for 30 m × 30 m grid cells throughout the conterminous United States and 10 m × 10 m grid cells for selected regions. The horizontal accuracy for location of the CRN stations is roughly +/−6 m (M. Hall 2004, personal communication). Thus, the CRN stations can be correctly located within the appropriate NED grid cell or, at worst, an adjacent grid cell. Comparisons of the NED data with elevation data from over 5800 National Geodetic Survey GPS benchmark locations within the conterminous United States resulted in an rmse of 2.6 m (D. Gesch 2004, personal communication). Elevation differences between the station pairs included in this study ranged from 6.5 m (Stillwater stations) to 169.8 m (Wolf Point).

The Lincoln difference in unadjusted mean temperature of 0.30°C and elevation difference of 0.0552 km resulted in an ELR of (0.30/0.0552 = 5.4) 5.4°C km^{-1}. The ELR derived from the station latitude-adjusted mean temperature difference of 0.16°C was 2.9°C km^{-1} (Table 3). As a result of the greater observed mean temperature at the station with the higher elevation

TABLE 2. Annual observed differences in paired station minimum, maximum, and mean temperatures (°C) derived from unadjusted station temperatures and differences in the fully adjusted mean annual temperatures. The number of daily observations (n) associated with each station is also indicated. The fully adjusted mean values are derived from application of the latitude and elevation adjustments in Table 1 to the unadjusted mean values of each station pair. Bold values indicate significant differences in the unadjusted temperatures, $p \leq 0.1$. Insufficient data were available to test for significant differences in the fully adjusted mean values.

	Unadjusted				Fully adjusted
	Min	Max	Mean	n	mean
Asheville	**−1.28**	**0.21**	**–0.53**	336	–0.37
Durham	**0.41**	**–0.26**	**0.07**	305	0.21
Lincoln	**0.85**	**–0.24**	**0.30**	335	0.45
Stillwater	**0.78**	**0.29**	**0.54**	348	0.59
Wolf Point	**2.33**	**–1.75**	**0.29**	301	1.35

(11SW), the lapse rate is positive (increase in temperature with height), rather than the normally observed negative lapse rate (decrease in temperature with height).

The unadjusted annual mean ELR values of the other station pairs ranged from –30.3°C km^{-1} for the Asheville pairs to 83.1°C km^{-1} for the Stillwater pairs (Table 3). An estimate of the location (horizontal and vertical) error associated with the ELR values was derived from the maximum and minimum elevations of the eight grid cells surrounding the grid cell in which the station was assumed to be located. The 2.6-m rms associated with the NED estimates of station elevation was used to assess the variation in ELR that might be due to the variation in estimated station elevation. Each station pair had 2.6 m (the NED rmse value) added to the elevation of the station with the higher estimate of elevation (out of the elevations for the grid cell where the station was assumed to be located and the eight surrounding grid cells) and 2.6 m subtracted from the elevation of the station with the lower elevation (of the nine total grid cells associated with the station). Additionally, each station pair had 2.6 m subtracted from the elevation of the station with the higher estimate of elevation (again, out of the nine total grid cells associated with a station) and 2.6 m added to the elevation of the station with the lower estimate. The results of this analysis (Table 3) indicate that even when an approximation of the potential variation in location is included in estimates of the ELR, only one station exhibits a negative ELR.

All ELR values (Table 3), unadjusted or latitude adjusted, were different from the lapse rate value of –5.3°C km^{-1} recommended to adjust station temperatures for elevation differences (Peterson 2003). The –5.3.°C km^{-1} ELR is an average of summer (−6.6°C km^{-1}) and winter (−4.0°C km^{-1}) values presented in Landsberg (1945). The derivation of these values is not reported in Landsberg (1945). Landsberg does mention that the annual mean global value (−4.9°C km^{-1}) is

TABLE 3. Annual ELR values (°C km^{-1}) for unadjusted and latitude-adjusted mean temperatures for station pairs. Estimated range of ELR values, based on estimated error of NED elevation data and potential station location error, is included in parentheses.

City	ELR (°C km^{-1}) Unadjusted	Latitude adjusted
Asheville	−30.3 (−68.8 to –19.4)	−26.3 (−59.7 to –16.8)
Durham	4.4 (2.9 to 9.4)	8.3 (5.4 to 17.6)
Lincoln	5.4 (4.9 to 6.4)	2.9 (2.6 to 3.4)
Stillwater	83.1 (43.9 to 675)	86.2 (45.5 to 700)
Wolf Point	1.7 (1.6 to 1.8)	2.6 (2.5 to 2.7)

valid up to 3.6 km; however, these values are all similar to reported saturation–adiabatic lapse rates (e.g., −4 to –7°C km^{-1}; Geer 1996, p. 195). Clearly, a lapse rate derived from observations in an atmosphere above the first several meters nearest the surface could not be expected to account for the microclimate influences on observed near-surface temperatures. These results (Table 3) suggest that the use of a constant lapse rate, however derived, may not be appropriate for adjustment of temperatures recorded at observation sites of varied elevations, but within 2 m of the land surface layer.

Another consideration in computation of lapse rates might be the use of average temperatures computed from maximum and minimum temperatures. Optimally, a lapse rate between a pair of stations would be derived for temperatures observed for the same time interval (e.g., hourly observations) rather than using mean temperatures computed from maximum and minimum temperatures that could have been observed at different times (e.g., Fig. 1). ELR values were derived for the Lincoln pair of stations based on hourly temperature values that were then averaged for daily, monthly, and annual intervals. The hourly ELR values between the stations varied considerably (Fig. 4) and generally displayed an inverse relationship to the wind speed observed at the stations. The unadjusted mean annual ELR for the Lincoln CRN pair derived from hourly computation of the ELR was 3.6°C km^{-1}, compared to the value of 5.4°C km^{-1} based on daily maximum and minimum temperatures.

The microclimatic factors and land surface influences can, as demonstrated, appear to dominate the factors that can influence temperatures observed at nearby stations. The influence on temperature due to changes in the elevation of the land surface between stations, in particular, can be difficult to model. The Daymet model (http://daymet.org/) of Thornton et al. (1997) provides estimates of temperatures at 1-km spatial resolution over the conterminous United States. These estimates include computation of lapse rates between observation stations to permit estimation of temperatures at grid cells of varied elevations between the stations. One of the developers of the model (S. W. Running 2003, per-

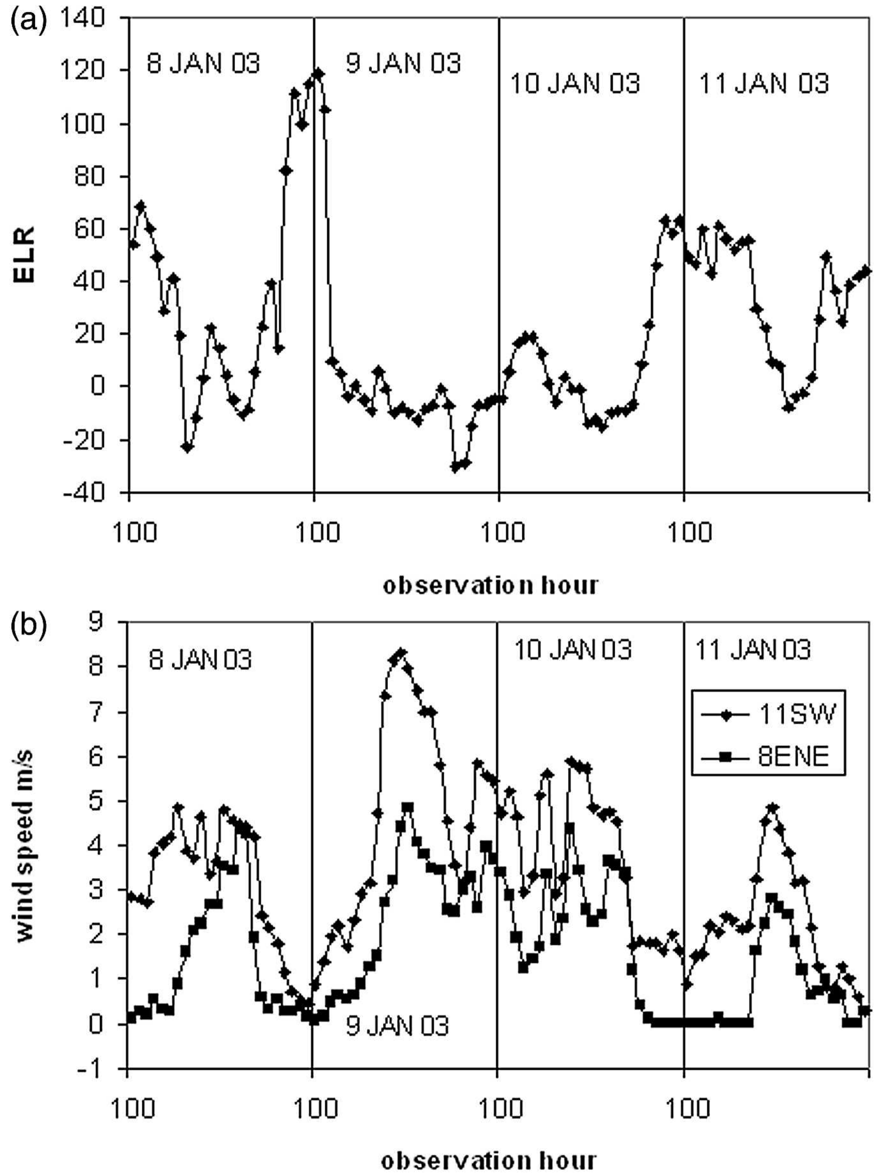

FIG. 4. (top) ELR (°C km^{-1}) and (bottom) wind speed observed for the Lincoln stations from 8 to 11 Jan 2003.

sonal communication) cautioned that the elevation-based estimates of temperature for stations and grid cells with less than 300 m of elevation difference can be overwhelmed by other factors for example, "prevailing wind patterns, nocturnal cold air inversions, humidity differences, and even local land cover." The local microclimate effects would certainly seem to dominate the elevation differences of the CRN station pairs examined in this study. These results are consistent with recent observations and postulations of others (e.g., Stohlgren et al. 1998; Kalnay and Cai 2003; Peterson 2003; Davey and Pielke 2004) related to the potential for local microclimate effects to dominate other, for example, large-scale, effects on temperature observations.

4. Summary and conclusions

Pairs of stations included in the Climate Reference Network of stations were examined for differences in minimum, maximum, and mean temperatures. Comparisons between these stations are fairly unique as there are no biases in the data records because of differences in instrumentation or time of observation. Significant differences were found in the annual minimum, maximum, and mean temperatures of paired CRN stations for all five pairs of stations. Adjustments for latitude and elevation differences contributed to greater differences in mean annual temperature than found in the unadjusted data for four of the five stations. Mean lapse rates computed between the temperatures observed at the stations were different from a constant value, whether or not latitude adjustments were made to the data. The results suggest that microclimate influences on temperatures observed at nearby (horizontally and vertically) stations are potentially much greater than influences that might be due to latitude or elevation differences between the stations.

Acknowledgments. The author acknowledges the assistance of Dr. Bruce Baker, Chief Scientist of the CRN at NOAA's National Climatic Data Center, for assistance with data acquisition and review of this manuscript. Dr. Kenneth Hubbard of the University of Nebraska at Lincoln provided helpful detailed information about the CRN stations near Lincoln. The author is thankful to the reviewers of this manuscript as their comments improved the manuscript content. This study was partially supported by NOAA's Office of Global Programs. The manuscript contents are solely the opinion of the author and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

REFERENCES

Davey, C. A., and R. A. Pielke Sr., 2005: Microclimate exposures of surface-based weather stations—Implications for the assessment of long-term temperature trends. *Bull. Amer. Meteor. Soc.,* in press.

Gallo, K. P., and T. W. Owen, 1999: Satellite-based adjustments for the urban heat island temperature bias. *J. Appl. Meteor.,* **38,** 806–813.

——, A. L. McNab, T. R. Karl, J. F. Brown, J. J. Hood, and J. D. Tarpley, 1993: The use of NOAA AVHRR data for assessment of the urban heat island effect. *J. Appl. Meteor.,* **32,** 899–908.

Geer, I. W., Ed., 1996: *Glossary of Weather and Climate with Related Oceanic and Hydrologic Terms*. Amer. Meteor. Soc., 272 pp.

Gesch, D., M. Oimoen, S. Greenlee, C. Nelson, M. Steuck, and D. Tyler, 2002: The National Elevation Dataset. *Photogramm. Eng. Remote Sens.,* **68,** 5–11.

Kalnay, E., and M. Cai, 2003: Impact of urbanization and land-use change on climate. *Nature,* **423,** 528–531.

Karl, T. R., H. F. Diaz, and G. Kukla, 1988: Urbanization: Its detection and effect in the United States climate record. *J. Climate,* **1,** 1099–1123.

Kukla, G., J. Gavin, and T. R. Karl, 1986: Urban warming. *J. Climate Appl. Meteor.,* **25,** 1265–1270.

Landsberg, H., 1945: Climatology. *Handbook of Meteorology*, F. A. Berry Jr., E. Bollay, and N. R. Beers, Eds., McGraw-Hill, 927–998.

NOAA/NESDIS, 2002: Climate Reference Network (CRN) site information handbook. NOAA/NESDIS National Climatic Data Center Doc. NOAA-CRN/OSD-2002-0002R0UD0, Asheville, NC, 19 pp. [Available online at http://www1.ncdc.noaa.gov/pub/data/uscrn/documentation/program/X030FullDocumentD0.pdf.]

Peterson, T. C., 2003: Assessment of urban versus rural in situ surface temperatures in the contiguous United States: No difference found. *J. Climate,* **16,** 2941–2959.

Stohlgren, T. J., T. N. Chase, R. A. Pielke Sr., T. G. F. Kittel, and J. Baron, 1998: Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. *Global Change Biol.,* **4,** 495–504.

Thornton, P. E., S. W. Running, and M. A. White, 1997: Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.,* **190,** 214–251.